Possibility of hydrological connectivity between Manasarovar Lake and Gangotri Glacier

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Considering the hydrological and religious significance of the Ganga River and the Manasarovar Lake in India, the present study has been devised to investigate the data related to the place of origin of the Ganges and to investigate the likely connection between waters of the two systems. Satellite data was employed to develop maps and find out the possibility of surface connectivity, whereas isotopic and chemical data, obtained from the field samplings and the published research literatures were used to investigate the possibility of subsurface connectivity of the Gangotri Glacier water with that of the Manasarovar Lake. Topographically, both the water systems are located in different catchment zones, separated by high mountain ridges; rejecting any possibility for the surface connectivity. Similarly, there are significant variations in isotopic and physiochemical properties of the water, suggesting no possibility of surface or sub-surface connectivity between water of the two systems.

Keywords: Ganga River, Gangotri Glacier, Mansarovar Lake, satellite data, stable isotope.

THE Ganga River, the most sacred river to the Hindu, supports millions of people residing in its extensive catchment area of 1,086,000 sq. km and forms the main artery carrying the lifeblood of riparian states of northern India[1–3]. There are different views on the origin of the Ganges[4]. According to popular belief, the Gangotri Glacier in the Uttarkashi district of Uttarakhand State in India is considered to be the source of the Ganga River[5,6]. However, many views suggest that the Manasarovar Lake in Tibet is the genesis of the Ganga River[7].

These assumptions/beliefs could be validated only by studying the hydrological connectivity between the water of the two systems, i.e. Mansarovar Lake and Gomukh (Gangotri Glacier). In literature, a range of techniques and approaches have been used to study the hydrological connectivity between water of the two systems[8]. But, topographical analysis[9–11] and hydrochemical tracers are among the most commonly employed techniques[12,13]. The understanding of surface topography (relief, slope and aspect) is vital in hydrological studies, as it controls flow path and direction. Further, the study of interaction between topographic controls and catchment processes provides an insight into understanding the dynamics of hydrological connectivity[14]. A digital elevation model (DEM), in combination with other spatial data, is widely used for topography and flow gradient related analyses[15–17]. Similarly, hydro-chemical tracers are used for detection of fissured rock seepage flow[18], the study of surface–groundwater interactions[19] and groundwater dynamics[20]. Therefore, in the present study, an effort has been made to investigate the data related to the source of origin of the Ganga River and to investigate the likely connection between the water of the two systems.

Geographical description of study area

Manasarovar Lake (also known Mapam Yumco), confined between geographic coordinates 30°34′–30°47′N and 81°22′–81°37′E, is located in Pulan County, Ali (Ngari) district of Tibet[21]. The total surface area and the storage capacity of the lake are 412 sq. km and 20×10^9 m^3 respectively[21]. The catchment area of the lake is placed between the Trans-Himalaya in the north and the Himalayas in the south (Figure 1). Manasarovar Lake is connected with Rakshas-Tal, the provenance of the Satluj River, through *Ganga Chhu* channel.

The Gangotri Glacier, the largest glacier (length: 30.20 km; width: 0.20–2.35 km; area: 86.32 sq. km) of the Garhwal Himalaya, is located at an altitude of ~4000 m in the Uttarkashi district of Uttarakhand. The Gangotri, together with other glaciers, forms a cluster of glaciers known as Gangotri glacier system (GGS) with a glacierized area of about 286 sq. km (ref. 22). Bhagirathi River originating from the snout of the Gangotri Glacier

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(Gomukh) joins the Alaknanda River at Devprayag; subsequently the combined flow is known as the Ganga River. Alaknanda emanates from the Sathopanth Glacier (length: 21 km; width: 0.75 km; area: 13 sq. km) at an altitude of 3858 m (Figure 1).

Materials and methods

We have used three types of data in this study; DEM (satellite data), stable isotopes (δ^2H and δ^{18}O) and physicochemical data of water. DEM data of 90 m resolution was obtained from the website of shuttle radar topographic mission (SRTM) (https://lta.cr.usgs.gov/SRTMs). The data, available in tiles of 5° × 5° and GeoTIFF format, are in a geographic coordinate system with a WGS84 datum. The downloaded tiles of the DEMs were exported to IMG format under Erdas Imagine 2010 platform. Further, these were mosaicked and re-projected on Projected Universal Transverse Mercator Projection (Zone N 44) and WGS84 datum. Similarly, we collected meltwater samples emanating from the Gangotri Glacier (2005 and 2016) and the Satopanth Glacier (2017). The meltwater samples ($n = 334$) collected on a daily basis during the ablation period (May/June–September), were measured for δ^2H and δ^{18}O using a dual inlet isotope ratio mass spectrometer at the Nuclear Hydrology Laboratory, National Institute Hydrology, Roorkee, India. Few samples ($n = 20$) of rainwater were also collected during ablation in 2016 and analysed for δ^2H and δ^{18}O respectively. However, physicochemical data (including δ^2H and δ^{18}O for the Manasarovar Lake) used in this study were obtained from the literature survey.

Results and discussion

Interpretation from satellite data

Satellite data was used to develop maps and find out surface connectivity. The topography (relief) of the Manasarovar Lake and the Gangotri Glacier catchments is shown in Figure 1. Manasarovar is a nearly round-shaped lake located on the Tibetan Plateau. It is placed to the west of a ridgeline that separates it from the present day Ganga Basin. The Kailash (Gangdise) range marks it at furthermost north boundary. The linear distance between the Manasarovar Lake and the Gomukh is approximately 230 km. The catchment area of the lake is characterized by rugged topography where elevation ranges from 4245 to 5075 m. In contrast, the Gangotri Glacier and Sathopanth Glacier rest in the Greater Himalayan region, south of the Tibetan Plateau, where elevation ranges from 3000 to 7515 m.

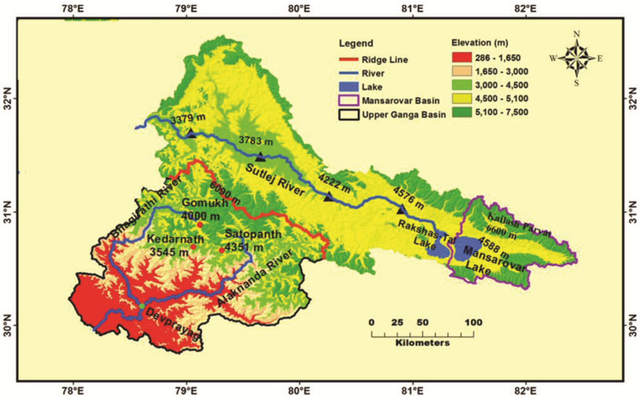

Figure 1. Location of the Manasarovar Lake, the Gangotri (Gomukh) and the Sathopanth Glaciers.

A longitudinal cross-section (L-section) line between the Gomukh and the Manasarovar Lake was drawn to see how the pattern in relief changes with distance from the Gomukh to the lake (Figure 2). It shows that both the water systems are located in different catchment zones and separated by high mountain ridges and narrow (deep) valleys. Although, the Manasarovar Lake is situated in a valley, relatively at a higher altitude than that of the Gomukh, a flow gradient is developed from the lake towards the Gomukh. But, in the present scenario, it is not feasible for the surface water emanating from the lake to reach the Gomukh, as it cannot flow without being trapped in nearby valleys and by overtopping the mountain ridges. This view is also held valid through the study of slope and drainage maps of the region which clearly show the flow pattern of the rivers and streams (Figure 3). Thus, the study of topographical analysis suggests that there is no possibility of surface connectivity between the water of the two systems.

Interpretation from isotope and physicochemical data

Isotope (δ^2H and δ^{18}O) and physicochemical data of water emanating from the Manasarovar Lake and

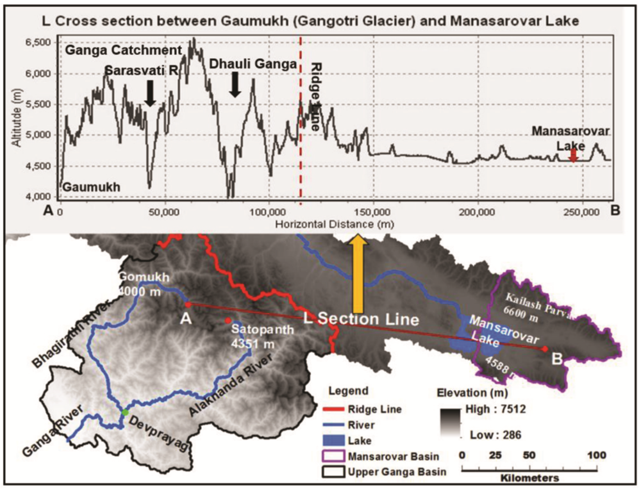

Figure 2. Cross section between the Gomukh (Gangotri Glacier) and the Manasarovar Lake.

Gangotri/Satopanth Glaciers have been analysed to investigate sub-surface connectivity. δ^{2}H in the lake water (collected in August 2005) is found to vary from –87.1‰ to –45.1‰ (average value –60.0‰) and from δ^{18}O –11.3‰ to –3.3‰ (average value –5.5‰)[21]. In another study conducted by Ren *et al.*[23], the value of δ^{2}H and δ^{18}O in the lake water (collected on 1 July 2012) was found to be –46.3‰ and –2.7‰, respectively. Similarly, δ^{2}H and δ^{18}O in rainfall (August 2005) occurring over the lake catchment range from –187.9‰ to –1.3‰ (average value –100‰) and –26.4‰ to –1.1‰ (average value –14.4‰) respectively. The stable isotopes (δ^{2}H and δ^{18}O) data of the lake water are plotted on an X–Y graph as shown in Figure 4 *a* with respect to the local meteoric water line (LMWL). The lake water samples cluster below the LMWL and show considerable differences concerning isotopic signatures (δ^{2}H and δ^{18}O). The best-fit regression line ($\delta^{2}H = 4.71 * \delta^{18}O - 34.03$), developed for the lake water also known as lake water line (LWL), intersects with the LMWL. This indicates that local precipitation is the source of lake water[21]. Further, the deviation in slope and intercept of the LWL (slope: 4.71, intercept: –34.03) from that of the LMWL (slope: 7.37, intercept: 6.26) implies that lake water holds signature of evaporative enrichment.

δ^{2}H in meltwater oozing out from the Gangotri Glacier is found to vary between –152.1‰ and –79.2‰ and δ^{18}O –21‰ and –11.7‰. δ^{2}H and δ^{18}O are in the range of –152.1‰ to –80.8‰ (average value –103.0‰) and –21‰ to –12.3‰ (average value –15.1‰) respectively, in 2005 –125.9‰ to –79.2‰ (average value –105.80‰) and –17.1‰ to –11.7‰ (average δ^{18}O value –14.9‰) respectively, in 2016. Similarly, δ^{2}H and δ^{18}O range from –167.1‰ to –57.3‰ (average value –84.0‰) and from –22.7‰ to –9.6‰ (average value –12.6‰) in meltwater of the Satopanth Glacier respectively. However, δ^{2}H and δ^{18}O in rainfall, in 2016, range from –163.6‰ to –47.5‰ (average value –119.7‰) and from –21.7‰ to –7.5‰ (average value –16.2‰) respectively. In line with this, the isotopic character of meltwater of the Yarlungzangbo (Bramhaputra) River has also been examined. Bramhaputra River originates from the Jiemayangzong Glacier (altitude: ~5100–5700 m), located to the east of Mansarovar Lake, in the northern slope of the western Himalaya. δ^{2}H and δ^{18}O in meltwater (collected on 16 July 2012) near the glacier are –104.9‰ and –14.6‰ respectively[23].

The δ^{2}H versus δ^{18}O plot of the Gangotri Glacier reveals that most of the water samples cluster on or above the LMWL (Figure 4 *b*). The best-fit regression line of the developed river water line (RWL) is $\delta^{2}H = 8.3 * \delta^{18}O + 20.7$). The RWL run parallel to the LMWL (slope: 8.2; intercept: 12.2), suggesting snow/glacier melt to be the dominant source of river water. The high slope and intercept values point to the contribution of low-temperature

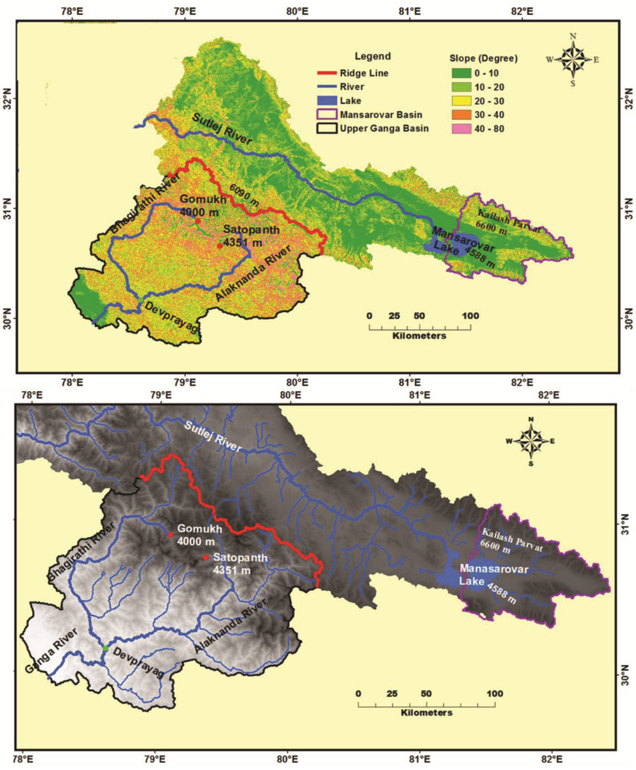

Figure 3. Map showing slope and major drainage network between catchments of the Upper Ganga Basin and the Manasarovar Lake.

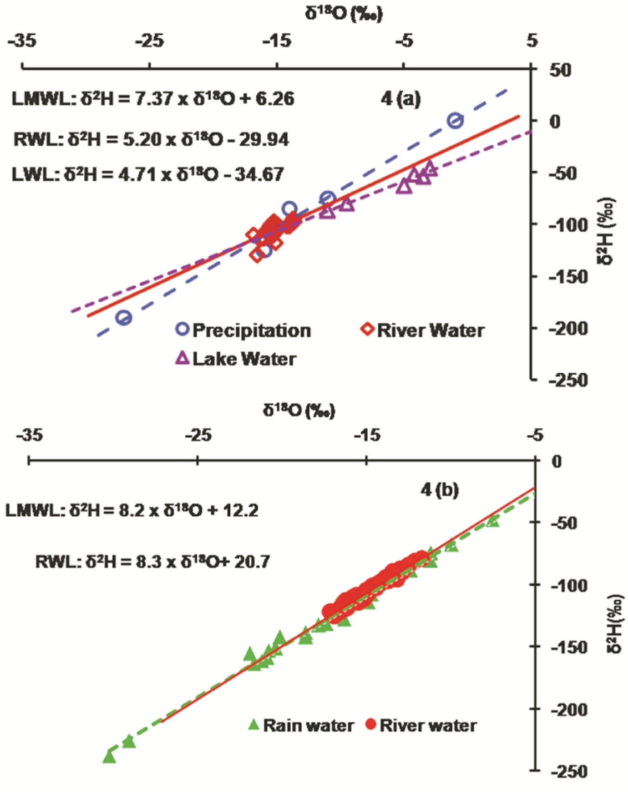

Figure 4. Isotopic comparison of water of the Manasarovar Lake and the Gangotri Glacier.

Table 1. Physicochemical characteristics of the Manasarovar Lake, and meltwater of the Bhagirathi River and the Alaknanda River

	Average concentration (mg/l, except pH)									
Source	pH	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	HCO_3^{-}	Cl^{-}	Reference
August 2005										
Mansarovar Lake	7.85	343.7	35.72	32.68	49.54	4.76	33.24	347.54	14.03	27
July 2004 and April 2005										
Bhagirathi near Gomukh	7.16	60.9	4.12	2.36	1.73	3.24	19.25	16.23	0.40	29
Bhagirathi near Gomukh	7.20	74.0	7.24	1.63	3.22	2.46	20.93	13.18	0.39	28
Alaknanda near Manna	7.17	73.0	7.02	0.72	2.58	1.33	8.45	34.16	2.0	

precipitation in the form of snow in the higher altitude areas, possibly of the western disturbance, as the elevation of the study area ranges from 3700 to 7100 m. This can be linked to kinetic fractionation involved in the process of snow formation at the low temperature[24].

The present results reveal that isotopic composition of meltwater of the Gangotri Glacier is more depleted (more negative) in δ^2H and δ^{18}O compared with the water of the Manasarovar Lake. This variation can be explained by considering the distinctive nature of these water bodies and climatic conditions prevailing there. Manasarovar (altitude: ~4588 m), an inland freshwater lake without outflow, has an extensive surface area of 412 sq. km and is characterized by a relatively longer residence period of water. The region comes under a semiarid zone, as moisture transported from the Indian Ocean is obstructed by the Himalaya in the south, and the Karakoram and Pamir stop moisture transport from the Mediterranean and the Atlantic Ocean in the west[23]. Therefore, it presents a unique characteristic of high plateau climate where the air is thin, and insolation is very intense, causing higher evaporation in lake water[21]. Additionally, the lake catchment receives precipitation from multiple sources of which a significant proportion is derived from recycled continental moisture sources[25]. However, the Gangotri Glacier gets the maximum of its annual precipitation from the two prominent moisture sources, i.e. Indian Ocean (in monsoon) and the Mediterranean Sea (in winter). This view is also supported by the results of deuterium excess or *d*-excess. The *d*-excess ($= \delta^2\text{H} - 8 * \delta^{18}\text{O}$) defined by Dansgaard[26] is a measure of the relative proportions of δ^{18}O and δ^2H contained in water. The *d*-excess in the Manasarovar Lake is found to vary from –26‰ to 1‰. However, it ranges between 12‰ and 22‰ in the meltwater of the Gangotri Glacier. The very low *d*-excess of the lake is due to more evaporation from the open water body or non-equilibrium fractionation of the lake water.

The analysis of physicochemical parameters (pH, EC, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, HCO_3^- and Cl^-) of water of both the systems (Manasarovar and Gangotri Glacier) also reveals differences in their physicochemical characteristics (Table 1). The pH, EC and TDS, measured for the lake water are relatively higher than that of the Bhagirathi and the Alaknanda rivers. Similarly, the overall ion concentrations were very high in Manasarovar Lake water as compared to the meltwater draining from the Bhagirathi and Alaknanda rivers. In the Manasarovar lake, the cation component is decreasing in the order of $Na^+ > Ca^{++} > Mg^{++} > K^+$ (ref. 27). However, in the Bhagirathi and Alaknanda River samples, the abundance order of cation are $Ca^{2+} > Mg^{2+} > K^+ > Na^+$ and $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ respectively[28,29]. In the lake water, Na^+ is the most dominant cation, representing 40.3% of the total cation content while K^+ is the least abundant, accounting for 3.8% of the total cation content. Ca^{2+} (35.72 mg/l) and Mg^{2+} (32.68 mg/l) are found in almost similar concentrations and accounting for 29.11% and 26.63%, of the total cation respectively. While in the Bhagirathi and Alaknanda river water, Ca^{2+} is the most dominant cation and on an average, varies from 36.0% to 60.3% of total cation charge (TZ^+), followed by Mg^{2+} (6.2 %–20.6%), K^+ (11.4–28.3%) and Na^+ (15.1–22.1%).

Among the anions, HCO_3^- is the most abundant anion in the lake water and constitutes 88% of the total anion content and SO_4^{2-} and Cl^- ions are less abundant representing only 8.4% and 3.6% respectively. However, SO_4^{2-} and HCO_3^- are the most dominant anion in the Bhagirathi River at Gangotri and vary from 53.7% to 60.7% and 38.2% to 45.2% of total anion charge respectively[28,29]. The abundance order of anions in Bhagirathi River samples is found as follows: $SO_4^{2-} > HCO_3^- > Cl^-$. In the Alaknanda River water (at Mana), HCO_3^- (76.66%) is the most dominant anion, followed by SO_4^{2-} and Cl^-. Similarly, the Piper diagram (Figure 5) reveals that, on average, Gangotri and Alaknanda River waters belong to the category of mixed water type, considerable samples fall in Ca–SO_4^{2-}, Mg^- SO_4^{2-} and Ca–HCO_3 type, except a few samples which fall in Mg–HCO_3 type water region. In contrast, the lake water samples are found to be clustering in the region of Mg–HCO_3^- and marginally lying close to Na–HCO_3^-. However, a ternary diagram for the cations and anions plotted by Yao *et al.*[27], shows that most of the lake water samples cluster near the ($Na^+ + K^+$) and HCO_3^- endmembers respectively.

Thus, on comparing the results of these different studies, it can be concluded that the ion content of the Manasarovar Lake water is much higher than that of the Bhagirathi and Alaknanda River waters. Yao *et al.*[27] plotted Gibbs diagram and observed that content of TDS and Na^+ is higher in the lake water, indicating a larger effect of evaporative crystallization on Manasarovar Lake chemistry. While relatively high contribution of (Ca + Mg) to the total cations (TZ^+) and high (Ca + Mg)/(Na + K) ratio indicate the dominance of carbonate weathering as a major source of dissolved ions in the glacier meltwater[28,29], the high sulphate concentration in Bhagirathi River water may be due to pyrite dissolution in the bedrock[30] as well as due to the dissolution of sulphate minerals (gypsum and anhydrite). These results support the view of Meybeck[31] who described that meltwater draining from different glaciers is in equilibrium with bedrock terrain over which the glaciers flow.

Conclusion

The analysis of remote sensing data shows that both water systems (Manasarovar Lake and Gangotri Glacier) are located in different catchment zones, separated by high mountain ridges, and at present, there is no possibility of surface connectivity between the water of the two systems. Further, the analysis of isotope and chemical data imply that the signatures of lake water are not similar to that of the meltwater draining from the Gangotri Glacier. For example, $\delta^{18}O$ in the Manasarovar Lake water varies between –11.3‰ and –3.3‰, and in water draining from the glaciers from –21‰ to –11.7‰. It indicates that meltwater draining from the Gangotri Glacier has depleted value than that of the Manasarovar Lake. Similarly, from the physicochemical viewpoint, the lake water has 10–14 times higher concentrations of Na^+ and Mg^{++} than the meltwater. The K^+ and Ca^{2+} concentrations in lake water are measured at 4.76 and 35.72 mg/l which is much higher than that measured in the meltwater of the Bhagirathi (2.46 mg/l and 14.48 mg/l) and Alaknanda (1.33 mg/l and 7.02 mg/l) rivers. Among the anions, the concentrations of HCO_3^- in these rivers are found to be 13.18 mg/l (Bhagirathi River) and 34.16 mg/l (Alaknanda River), while in the lake water it is 347.54 mg/l. A similar pattern is also perceived for Cl^-. The lake water is rich in chloride, and its quantity is almost ten times than that in the meltwater of the rivers.

A significant difference in *d*-excess of the two water bodies is also observed. The *d*-excess in the Manasarovar Lake is found to vary from –26‰ to 1‰. However, it ranges between 12‰ and 22‰ in the meltwater of the Gangotri Glacier. This suggests that contribution of the Manasarovar Lake, in meltwater, draining from Gangotri Glacier cannot be established at present. If the lake were the source of meltwater at Gomukh through seepage or subsurface connectivity, the *d*-excess would have been the same. Thus, at present, no possible connection between water of the two systems (the Manasarovar Lake and the Bhagirathi River at Gomukh) is apparent. Chemical and isotopic observations available for the Manasarovar Lake are limited and available only for the lake surface and for a specific time. There is also no depth-wise observation of the lake. Therefore, the present study encourages further investigation in all aspects including aspects of the subsurface flow channels with high-frequency data to understand the surface and subsurface connectivity between Manasarovar and Gomukh.

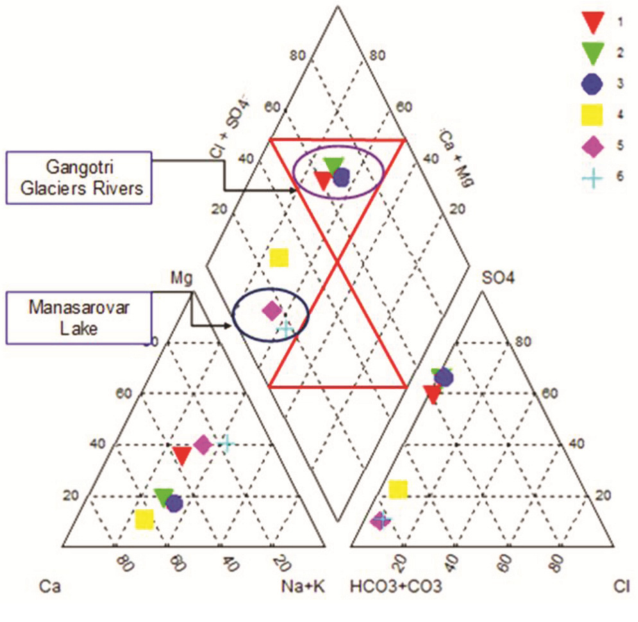

Figure 5. Piper plot for showing different water facies for the Manasarovar Lake and the Gangotri Glacier.

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